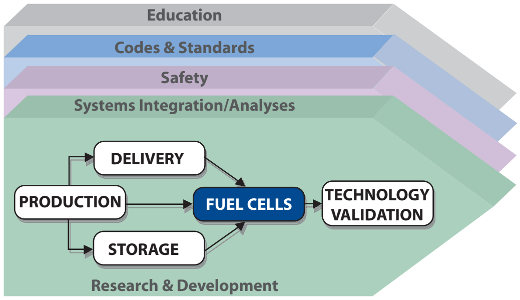
3.4 Fuel Cells



Fuel cells have the potential to replace the internal combustion engine in vehicles and to provide power in stationary and portable power applications because they are energy efficient, clean and fuel flexible. Hydrogen or any hydrogen-rich fuel can be used by this emerging technology. For transportation applications, the Program is focusing on direct hydrogen fuel cells, in which hydrogen is stored on board and is supplied by a hydrogen generation, delivery, and fueling infrastructure. This infrastructure is being developed in parallel with the fuel cell development efforts.

Prior to August 2004, significant fuel cell activity resources supported on-board vehicle fuel processing, where hydrogen could be produced from fuels such as gasoline, methanol, ethanol, natural gas or other hydrocarbons, supplied by the existing infrastructure. Subsequently, DOE has decided to discontinue on-board fuel processing R&D. Further discussion relating to this decision can be found in Programmatic Status (section 3.4.3).

For distributed generation applications, fuel cell systems will likely be fueled with natural gas or liquefied petroleum gas (LPG, consisting predominantly of propane) in the near term and in the longer term by renewable fuels. Fuel cells for auxiliary power units in trucks will use either diesel or LPG and recreational vehicles will be powered by LPG alone. In small consumer electronics, hydrogen or methanol will be the fuel of choice for fuel cell systems.

3.4.1 Technical Goal and Objectives

Goal

Develop and demonstrate fuel cell power system technologies for transportation, stationary and portable applications.

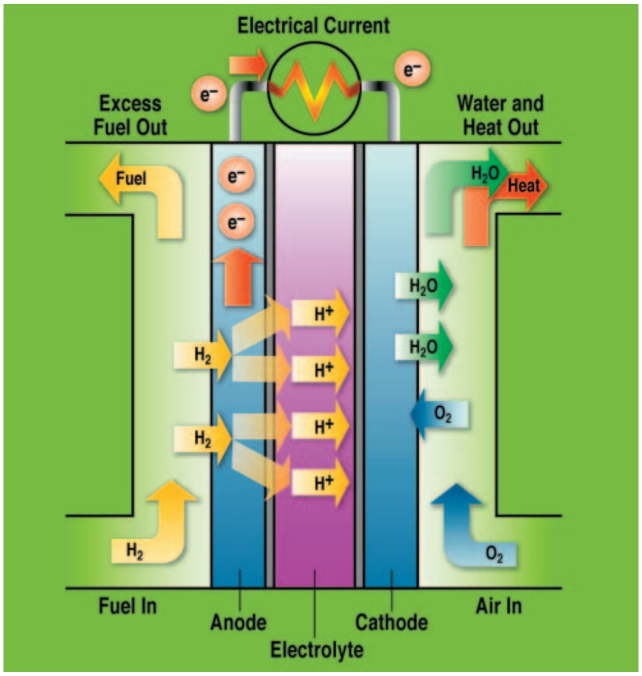
Objectives

- By 2010, develop a 60% peak-efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of \$45/kW; by 2015, a cost of \$30/kW.
- By 2010, develop a distributed generation PEM fuel cell system operating on natural gas or LPG that achieves 40% electrical efficiency and 40,000 hours durability at \$400-\$750/kW.
- By 2010, develop a fuel cell system for consumer electronics with (<50 W) an energy density of 1,000 Wh/L.
- By 2010, develop a fuel cell system for auxiliary power units (3-30 kW) with a specific power of 100 W/kg and a power density of 100 W/L.

3.4.2 Technical Approach

Fuel cell research and development will emphasize high efficiency and durability and low material and manufacturing costs of the fuel cell stack, and balance-of-plant components like air compressors, and sensors and controls. However, each application – light vehicle transportation, auxiliary power units (APUs) for heavy duty vehicles, stationary, and portable power for consumer electronics—requires a different approach for technology development. Specifically, polymer electrolyte membrane (PEM) fuel cells, shown in Figure 3.4.1, are the current focus for light duty vehicles because they have fast start capability and operate at low temperatures. Solid oxide fuel cells (SOFCs) generate more power (have higher power density) and are more applicable as APUs on heavy duty vehicles where systems may run for extended periods without frequent start and stop cycles. Direct methanol fuel cells (DMFCs) are well suited for portable power applications in consumer electronic devices where the power requirements are low and the cost targets are not as stringent as for transportation applications. The emphasis of the Program is fuel replacement for light duty vehicles to reduce our nation's dependence on imported petroleum. In addition to this transportation fuel cell application focus, i.e. direct hydrogen fuel cell vehicles, the program also supports stationary, portable power and auxiliary power applications to a limited degree where earlier market entry would assist in the development of a fuel cell manufacturing base.

Figure 3.4.1. Polymer Electrolyte Membrane Fuel Cell



To meet the efficiency, durability and cost requirements for fuel cells, research and development will focus on identifying less expensive new materials and novel fabrication methods for membranes, catalysts and bipolar plates. Testing of these new materials and fabrication methods will be carried out by industry, national laboratories and universities. Progress has already been made in developing fuel cell membranes that are capable of operating at 120^{o}C or above for better thermal management. In addition, advances continue to be made in minimizing precious metal loading, assessing and improving component durability, and developing thin catalyst coatings for membranes, high-volume fabrication processes, and highly conductive, gas-impermeable bipolar plates.

In comparison to prior years, much less emphasis will be placed on fuel cell systems development. Instead, R&D efforts will focus on materials, components, and enabling technologies for low-cost fuel cell power systems operating on direct hydrogen for transportation, reformed natural gas or LPG for stationary applications, reformed diesel or LPG for auxilary power and methanol for consumer electronic applications. Validation of fuel cell technology targets related to performance, reliability, durability and environmental benefits will be conducted in the Hydrogen Infrastructure and Fuel Cell Vehicle Learning Demonstration. The Technology Validation Program element (see section 3.5) will provide data under real-world conditions and, in turn, supply valuable fuel cell results to help refine and direct future activities for fuel cell R&D.

Fuel cell R&D will taper and eventually end once the technical targets are achieved and the technologies are commercially adopted. When major cost milestones are met for stationary and transportation applications, the R&D in those areas will conclude. If specific cost performance and durability issues remain, R&D could be extended, assuming the cost of a continued effort is justified by the anticipated benefits.

3.4.3 Programmatic Status

As mentioned earlier, the Fuel Cell team conducted a review of on-board fuel processing for transportation applications during 2004. In August of 2004 DOE decided to discontinue on-board fuel processing R&D.

Specific criteria for the on-board fuel processing decision are shown in Table 3.4.1.

Table 3.4.1 DOE On-Board Fuel Processing Go/No-Go Criteria

Attribute	Units	2004 Demo Criteria	Current Status (2/2004)	Ultimate Target	Probability of Reaching Ultimate Target
Durability	hours	2000 and >50 stop/starts	1000	5,000 and 20,000 starts	medium
Power Density	W_e/L	700	700	2,000	medium
Efficiency	%	78	78	>80	high
Start-up Energy	MJ/50 kW_e	<2	7	<2	low
Start-up Time (+20°C)	sec	<60 to 90% traction power	600	<30 to 90% traction power <2 to 10%	low
Transient Response	sec	<5, 10% to 90% and 90% to 10%	10	<1, 10% to 90%, and 90% to 10%	low
Turndown	ratio	20:1	20:1	> 50:1	medium
Sulfur Content	ppb	<50 out from 30 ppm in	130	<10 out from 30 ppm in	medium
Cost	$/kW_e$	n/a	65	<10	low

A review of on-board fuel processing activities was conducted. It concluded that, based on the current state of the technology, it was unlikely that on-board fuel processing would improve sufficiently to support the transition to a hydrogen economy. This decision included consideration of the following key factors:

- The Hydrogen Fuel Initiative accelerated hydrogen technology development and lessened the contribution that on-board fuel processing could make as a transitional technology;
- Compared to today's gasoline hybrid electric vehicle technologies, on-board fuel processing for fuel cell vehicles offered only marginal improvements in efficiency and emissions; and
- Existing technical and cost targets cannot be met with current fuel processing technologies and no clear path forward has been articulated for meeting the difficult criteria associated with full implementation/integration of on-board fuel processing in fuel cell vehicles.

While on-board fuel processing activities will be terminated, the fuel processing activity will continue. Development projects supporting on-board fuel processing systems will be terminated or redirected. The Program continues to develop fuel processors for stationary applications and to develop fundamental catalysts suitable for a variety of fuel processing applications, such as auxiliary power applications (APU). Fuel processing research for APU will support the 21st Century Truck Initiative and the Office of Fossil Energy's Solid-State Energy Conversion Alliance (SECA).

Current Activities.

Table 3.4.2 summarizes the current activities of the Fuel Cells Program element.

Table 3.4.2 Current Fuel Cell Activities

Challenge	Approach	Activities
Transportation Systems		
Efficient, cost-effective compressor / expander technologies and thermal/water management systems	• New engineering approaches to compressor/expander technologies (e.g. lubricant-free) • Improve efficiencies and performance • Reduce weight and cost • Develop thermal and water management systems	• **Honeywell:** Integrated thermal/water management system that efficiently uses the fuel cell waste heat and water • **Mechanology:** Toroidal intersecting vane compressor/expander module • **Honeywell:** Turbo compressor for operation in PEMFC transportation systems • **Advanced Fluids (SBIR):** Improved coolant (water/glycol with nanoparticles) for use in PEM fuel cell systems • **Oak Ridge National Laboratory:** Carbon foam technology to recover water from fuel cell exhaust and humidify inlet air
Effective, reliable physical and chemical sensors	• Develop accurate, reliable, fast-responding sensors to measure physical properties and chemical species. • Reduce cost and footprint	• **Honeywell:** Physical sensor technology meeting customer requirements • **UTC Fuel Cells:** Physical and chemical sensors for fuel cell application • **Lawrence Livermore National Laboratory:** Hydrogen safety and performance sensors • **Oak Ridge National Laboratory:** Fiber optic temperature sensor
System and market analysis	• Assess potential for cost reductions to reach customer-acceptable levels • Evaluate the potential market demand and economics of fuel cell systems	• **National Renewable Energy Laboratory:** Fuel cell vehicle system analysis, trade-offs and optimization[a] • **New project:** Cost analysis of fuel cell systems[a] • **Argonne National Lab:** System analysis, trade-offs and optimization[a]
Stationary Systems		
High-temperature membranes for stationary applications	• Development of high-temperature membranes to facilitate combined heat and power applications meeting 40,000 hour durability requirement	• **Plug Power:** Poly-benzimidazole membranes
Stationary fuel cell system development and demonstrations	• Develop and demonstrate integrated systems for distributed generation and back-up power	• **UTC Fuel Cells:** Distributed generation • **Plug Power:** Back-up power • **IdaTech:** Combined heat and power • **National Renewable Energy Laboratory:** Computer aided engineering (CAE) for durability of fuel cell components[a]
System and market analysis	• Perform economic analysis of fuel cells and their associated markets	• **Battelle:** Economic analysis of stationary fuel cell markets[a]

[a] Also listed in Systems Analysis Table 5.4.1.

Fuel Processors		
Distributed natural gas or LPG fueled	• Develop technology for reforming natural gas or LPG • Develop advanced catalysts	• **Nuvera:** Advanced reforming module for stationary applications • **ChevronTexaco:** Sorption- enhanced reformer for low-CO hydrogen production • **Argonne National Laboratory:** Develop advanced fuel processing and catalyst technology • **Oak Ridge National Laboratory:** Catalytic oxidation for hydrogen sulfide removal
Efficient fuel-flexible fuel processors. Transportation applications will end in FY2005	• Reduce cost, weight, and size • Simplify systems and improve efficiency	• **Catalytica:** New catalyst, plate-based reactor for gasoline steam reforming • **University of Michigan:** Microchannel fuel processing
Stack Components		
Low-cost, durable plates, membranes, catalysts, membrane electrode assemblies (MEAs), and high temperature membranes	• Develop new, lower-cost, longer-life materials • Investigate new MEA configurations and low cost catalyses • Determine fuel/air contaminant thresholds • Develop MEAs that tolerate excursions to 120 ºC and/or operate at RH 25-50%. • Develop membranes that tolerate -40ºC and fuel cells that start up at -20ºC. • Evaluate catalyst recycling and reuse technologies	• **3M:** Advanced MEAs for 120ºC operation and low cost manufacturing methods • **DeNora/DuPont:** New cathode alloys, high temperature MEAs with increased kinetics • **UTC Fuel Cells:** High temperature membranes with improved kinetics and CO tolerance • **DuPont:** Perfluorosulfonic acid membranes with extended lifetimes • **3M:** Perfluorosulfonic acid membranes with extended lifetimes • **Arkema (formerly Atofina Chemicals, Inc.):** Polyvinylidenefluoride-based membranes • **Cabot Superior Micropowders:** New cathode catalysts and structures for low platinum loading • **3M:** Innovative low cost technology to synthesize new non-precious metal catalysts and their supports • **University of S. Carolina:** Metallic nanoclusters as PEM fuel cell catalysts • **Ballard:** Metal/chalcogen based cathode catalysts • **Ion Power:** Catalyst coated fuel cell membrane and catalyst coated fuel processing component recycling and/or re-manufacture/reuse • **Engelhard:** Recover and recycle precious metals • **Porvair:** Pre-pilot scale production of net shape molded low cost carbon/carbon composite bipolar plates • **Oak Ridge National Laboratory:** Metallic bipolar plate alloy using thermal nitriding technology • **Los Alamos National Laboratory:** Advanced membranes, non-precious metal catalysts, and electrode technologies • **Argonne National Laboratory:** Advanced membranes and non-precious metal catalysts • **Lawrence Berkeley National Laboratory:** New electrocatalysts using materials-by-design approach • **Oak Ridge National Laboratory:** Characterize structural changes in membrane • **National Institute of Standards and Technology:** Characterize water transport in membrane • **Naval Research Laboratory:** Develop metal oxides as catalyst supports to reduce platinum loading • **Brookhaven National Laboratory:** Low platinum loading catalysts • **Case Western Reserve University:** Novel concepts for high-temperature/low humidity membrane application • **Los Alamos National Laboratory:** Investigate impact of freeze on the performance and durability of specific fuel cell components • **T/J Technologies (SBIR):** Low-cost polyphenylsulfonic acid (PPSA) membrane • **Farassis Energy (SBIR):** Low-cost cathode catalysts using novel combinatorial screening • **Nuvant (SBIR):** Low-cost cathode catalysts using high throughput, rapid screening methods • **Pacific Fuel Cell Corp. (STTR):** Nanocomposite membranes for high temperature PEMFCs

Portable Power/APUs/Off-Road Applications		
Auxiliary Power Unit (APU) system for heavy truck application to reduce idling of the main heavy duty engine	• Analysis and design of SOFC APU system • Develop and test subsystem components • Perform system integration and packaging • Perform vehicle integration	• **Cummins Power Generation:** Design, develop and perform in-vehicle demonstration of a diesel-fueled SOFC power system • **Delphi:** Build and test a full APU system in a laboratory demonstration with simulated load cycles • **Pacific Northwest National Laboratory:** Dynamic systems model and analysis capability for SOFC for APU
Consumer Electronics System	• Design, develop, fabricate and validate fuel cell systems for small portable power applications, such as cell phones and computers	• **MTI Microfuel Cells:** DMFC prototype for consumer electronics • **Polyfuel Inc:** DMFC system for all-day, wireless computing • **Giner (SBIR):** 20W DMFC stack using combined mixed reactant configuration • **Microcell (SBIR):** 20W regenerative PEMFC system with metal hydride fuel storage • **Renew Power (I&I):** Powering cell phones with fuel cells using renewable fuels
System which will allow PEM fuel cells to operate in off-road applications	• Characterize the concentration and distribution of contaminants found in off-road environments • Determine the impact of contaminants on fuel cell performance • Design a filtration system to mitigate the impact of off-road contaminants	• **IdaTech:** Team with UC Davis, Donaldson, and Toro to design, build, and test a system for off-road application

All the current R&D activities focus on advanced concepts, enabling technologies and the technical challenges discussed in the following section.

3.4.4 Technical Challenges

Cost and durability are the major challenges to fuel cell commercialization. Size, weight, and thermal and water management are also barriers to the commercialization of fuel cells. For transportation applications, fuel cell technologies face more stringent cost and durability requirements. In stationary power applications, raising the operating temperature of PEMs to increase fuel cell performance will also improve heat and power cogeneration and overall system efficiency.

Transportation Systems

Fuel cell power systems must be reduced in cost before they can be competitive with gasoline internal combustion engines (ICEs). The cost for automotive ICE power plants is currently about $25-35/kW; a fuel cell system needs to cost less than $50/kW for the technology to be competitive.

The durability of fuel cell systems has not been established. Fuel cell power systems will be required to be as durable and reliable as current automotive engines, i.e., 5,000 hour lifespan (150,000 miles equivalent) and able to function over the full range of vehicle operating conditions (-40° to +40° C).

Lightweight, compact on-board hydrogen storage systems and economically-viable hydrogen production and delivery also present challenges (see sections 3.1, 3.2 and 3.3).

Air management for fuel cell systems is a challenge because today's compressor technologies are not suitable for automotive fuel cell applications. In addition, thermal and water management for fuel cells are issues. Fuel cell operation at lower temperatures creates a small difference between the operating and ambient temperatures necessitating large heat exchangers and humidifiers. These components use part of the power that is produced, reducing overall system efficiency.

Finally, the size and weight of current fuel cell systems must be further reduced to meet the packaging requirements for automobiles. Size and weight reduction applies not only to the fuel cell stack (catalysts, membranes, gas diffusion media, bipolar plates), but also to the ancillary components (e.g., compressor/expander, heat exchangers, humidifiers, and sensors) making up the balance of plant.

Stationary/Distributed Generation Systems

Even though the specific performance requirements for stationary applications differ from transportation applications, some of the technical challenges are the same. For example, the overall cost of stationary fuel cell power systems must also be competitive with conventional technologies. Stationary systems, however, have an acceptable price point considerably higher than transportation systems; stationary systems are projected to cost $400–$750/kW for widespread commercialization and as much as $1000/kW for initial applications.

Performance of fuel cells for stationary applications for more than a few thousand hours must still be demonstrated but market acceptance of stationary applications will likely necessitate more than 40,000 hours of reliable operation at a temperature between -35^{o} C and 40^{o}C.

The low operating temperature of PEM fuel cells limits the amount of heat that can be effectively used in combined heat and power (CHP) applications. Technologies need to be developed that will allow higher operating temperatures and/or more effective heat recovery systems. Improved system designs that will enable CHP efficiencies exceeding 80% are also needed. Technologies that allow cooling to be provided from the heat rejected from stationary fuel cell systems (such as through regenerating desiccants in a desiccant cooling cycle) also need to be evaluated. Hybrid systems or other viable methods to decrease start-up times need to be developed for stationary fuel cell back-up power applications, which operate on direct hydrogen.

Portable Power Systems

Technical issues unique to fuel cell power systems for consumer electronics include: system and component miniaturization; small-scale fuel processing; microcompressors; fuel storage, distribution, and recharging for low-power applications; and system integration and packaging. Passive operation at near-ambient conditions and insensitivity to orientation are necessary for the low-power applications. Fuel delivery and storage, as well as safety, codes, and standards are important for consumer electronics and APUs.

3.4.4.1 Technical Targets

Tables 3.4.3 and 3.4.4 list the DOE technical targets specifically for integrated fuel cell power systems and PEM fuel cell stacks operating on direct hydrogen for transportation applications. These targets have been developed through the FreedomCAR and Fuel Partnership. Tables 3.4.5 through 3.4.7 list the DOE technical targets for stationary applications. The targets have been developed with input from developers of stationary fuel cell power systems, and have been established for small (3–25 kW) and large (50–250 kW) power levels. The targets assume a sulfur level in the natural gas or LPG of less than 6 ppm (average value). These R&D targets do not go beyond 2010 because stationary applications are closer to market than transportation applications. The 2010 targets are those that would be neccessary for successful commercialization.

Tables 3.4.8 and 3.4.9 list the DOE technical targets for consumer electronics, APUs, and truck refrigeration. The consumer electronics table is based on direct methanol fuel cell technology and the APUs and truck refrigeration table is based on solid oxide fuel cell technology and is consistent with the DOE Fossil Energy's SECA targets.

Tables 3.4.10 and 3.4.11 list DOE technical targets for automotive and stationary fuel cell system sensors and automotive compressor/expander units. All input powers to the compressor are specified for +40°C ambient air conditions and overall 50% system efficiency regardless of whether or not an expander is used. This requires that a higher stack voltage be used for those cases for which no expander is present; therefore, the stack must be slightly larger to compensate for such cases.

Tables 3.4.12 through 3.4.15 list DOE technical targets for fuel cell components: membranes, electrodes/catalysts, membrane electrode assemblies (MEAs), and bipolar plates. This reflects a shift in program focus from development of stack systems to more component-level research. These tables will assist component developers in evaluating progress without testing full systems.

Table 3.4.16 lists a first draft specification of hydrogen quality required as input into the fuel cell system.

All targets must be achieved simultaneously; however, status is not necessarily reported from a single system.

Table 3.4.3. Technical Targets: 80-kW_e (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen[a]

Characteristic	Units	2004 Status	2005	2010	2015
Energy efficiency[b] @ 25% of rated power	%	59	60	60	60
Energy efficiency @ rated power	%	50	50	50	50
Power density	W/L	450[c]	500	650	650
Specific power	W/kg	420[c]	500	650	650
Cost[d]	$/$kW_e$	120[e]	125	45	30
Transient response (time from 10% to 90% of rated power)	sec	1.5	2	1	1
Cold start–up time to 90% of rated power @–20°C ambient temp @+20°C ambient temp	 sec sec	 120 60	 60 30	 30 15	 30 15
Durability with cycling	hours	~1000[f]	2000	5000[g]	5000[g]
Survivability[h]	°C	–20	–30	–40	–40

[a] Targets exclude hydrogen storage.
[b] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.
[c] Based on corresponding data in Table 3.4.4 divided by 3 to account for ancillaries.
[d] Based on 2002$ and cost projected to high-volume (500,000 stacks per year).
[e] Based on 2004 TIAX Study and will be periodically updated.
[f] Durability is being evaluated through the Technology Validation activities. Steady-state durability is 9,000 hours.
[g] Includes typical drive cycle.
[h] Performance targets must be achieved at the end of 8-hour cold-soak at temperature.

Table 3.4.4. Technical Targets: 80-kW$_e$ (net) Transportation Fuel Cell Stacks Operating on Direct Hydrogen[a]

Characteristic	Units	2004 Status	2005	2010	2015
Stack power density[b]	W/L	1330[c]	1500	2000	2000
Stack specific power	W/kg	1260[c]	1500	2000	2000
Stack efficiency[d] @ 25% of rated power	%	65	65	65	65
Stack efficiency[d] @ rated power	%	55	55	55	55
Precious metal loading[e]	g/kW	1.3	2.7	0.3	0.2
Cost[f]	$/kW$_e$	75[g]	65	30	20
Durability with cycling	hours	~1000[h]	2000	5000[i]	5000[i]
Transient response (time for 10% to 90% of rated power)	sec	1	2	1	1
Cold startup time to 90% of rated power					
@ –20ºC ambient temperature	sec	120	60	30	30
@ +20ºC ambient temperature	sec	<60	30	15	15
Survivability[j]	ºC	–40	–30	–40	–40

[a] Excludes hydrogen storage and fuel cell ancillaries: thermal, water, air management systems.
[b] Power refers to net power (i.e., stack power minus auxiliary power). Volume is "box" volume, including dead space, and is defined as the water-displaced volume times 1.5 (packaging factor).
[c] Average from Fuel Cells 2000, http://www.fuelcells.org/info/charts.html#fcvs, April 2004
[d] Ratio of output DC energy to lower heating value of hydrogen fuel stream. Peak efficiency occurs at about 25% rated power. Assumes system efficiency is 92% of stack efficiency.
[e] Equivalent total precious metal loading (anode + cathode): 0.1 mg/cm^2 by 2010 at rated power. Precious metal target based on cost target of <$3/kW$_e$ precious metals in MEA [@$450/troy ounce ($15/g), <0.2 g/kW$_e$]
[f] Based on 2002$ and cost projected to high-volume (500,000 stacks per year).
[g] Based on 2004 TIAX Study and will be periodically updated.
[h] Durability is being evaluated through Technology Validation activities. Steady-state durability is 9,000 hours.
[i] Includes typical drive cycle.
[j] Performance targets must be achieved at the end of 8-hour cold-soak at temperature.

Table 3.4.5. Technical Targets[a]: Integrated Stationary PEM Fuel Cell Power Systems Operating on Natural Gas or LPG Containing 6 ppm Sulfur, Average

Characteristic	Units	Small (3–25 kW)			Large (50–250 kW)		
		2004 Status	2005	2010	2004 Status	2005	2010
Electrical Energy Efficiency[b] @ rated power	%	30[c]	32	35	30[c]	32	40
CHP Energy Efficiency[d] @ rated power	%	75[c]	75	80	75[c]	75	80
Cost[e]	$\$/kW_e$	3000	1500	1000	2500	1500	750
Transient Response Time (from 10% to 90% power)	msec	< 3	< 3	< 3	< 3	< 3	< 3
Cold Start-up Time[f] (to rated power @ −20°C ambient) Continuous use application	min	<90	<60	<30	<90	<60	<30
Survivability (min and max ambient temperature)	°C	–25 +40	–30 +40	–35 +40	–25 +40	–30 +40	–35 +40
Durability @ <10% rated power degradation	hour	>8,000	16,000	40,000	15,000	20,000	40,000
Noise	dB(A)	<70 @ 1 m	<65 @ 1 m	<60 @ 1 m	<65 @ 10 m	<60 @ 10 m	<55 @ 10 m
Emissions (Combined NO_x, CO, SO_x, Hydrocarbon, Particulates)	g/1000 kW_e	<15	<10	<9	<8	<2	<1.5

[a] Includes fuel processor, stack, and all ancillaries.
[b] Ratio of DC output energy to the LHV of the input fuel (natural gas or LPG) average value at rated power over life of power plant.
[c] For LPG, efficiencies are 1.5 percentage points lower than natural gas because the reforming process is more complex.
[d] Ratio of DC output energy plus recovered thermal energy to the LHV of the input fuel (natural gas or LPG) average value at rated power over life of power plant
[e] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for black start.
[f] Not applicable to backup power because this application does not use a fuel processor.

Table 3.4.6. Technical Targets: Stationary Fuel Cell Stack Systems Operating on Hydrogen-Containing Fuel from a Fuel Processor (Natural Gas or LPG)[a]

Characteristic	Units	2004 Status	2005	2010
Cost[b]				
Small (3–25 kW)	$\$/kW_e$	2000	1000	750
Large (50–250 kW)	$\$/kW_e$	1500	1000	530
Durability				
Small (3–25 kW)	hours	>8,000	16,000	40,000
Large (50–250 kW)	hours	15,000	20,000	40,000
Transient Response Time (for 10% to 90% of rated power)	sec	<3	<3	1
Cold Start–up Time (to rated power @ –20ºC)	min	<2	<1	<0.5
Survivability (min & max ambient temperature)	ºC	–25 +40	–30 +40	–35 +40
CO tolerance[c]				
steady state (with 2% max air bleed)	ppm	50	500	500
transient	ppm	100	500	1000

[a] Excludes fuel processing/delivery system. Includes fuel cell ancillaries: thermal, water, air management systems.

[b] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for black start.

[c] CO tolerance requirements assume capability of fuel processor to reduce CO. Targets for the stack CO tolerance are subject to trade-offs between reducing CO in the fuel processor and enhancing CO tolerance in the stack. It is assumed that H_2S is removed in the fuel processor.

Table 3.4.7. Technical Targets: Stationary Fuel Processors to Generate Hydrogen-Containing Fuel Gas from Natural Gas or LPG[a]

Characteristic	Units	2004 status	2005	2010
Cost[b]				
Small (3–25 kW)	$/kW_e$	1000	500	250
Large (50–250 kW)	$/kW_e$	1000	500	220
Cold Start–up Time[c] to rated power @ –20°C ambient	min	<90	<60	<30
Transient Response Time (for 10% to 90% power)	min	<5	<4	1
Durability[d]				
Small (3–25 kW)	hours	>8,000	16,000	40,000
Large (50–250 kW)	hours	15,000	20,000	40,000
Survivability (min and max ambient temperature)	°C	–25 +40	–30 +40	–35 +40
CO content in product stream[e]				
Steady State	ppm	10	5	1
Transient	ppm	100	50	25
H_2S content in product stream	ppbv (dry)	<10	<5	<2
NH_3 content in product stream	ppm	<1[f]	<0.1	<0.01

[a] Excludes fuel storage; includes controls, shift reactors, CO cleanup, heat exchangers.
[b] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for black start.
[c] Not applicable to backup power because this application does not use a fuel processor.
[d] Time between catalyst and major component replacement; performance targets must be achieved at the end of the durability period.
[e] Dependent on stack development (CO tolerance) progress.
[f] 1ppm is detection limit for NH_3.

Table 3.4.8. Technical Targets: Consumer Electronics (sub-Watt to 50-Watt)

Characteristic	Units	2004 Status	2006	2010
Specific Power	W/kg	10–20	30	100
Power Density	W/L	10–15	30	100
Energy Density	W–h/L	50–200	500	1,000
Cost	$/W	40[a]	5	3
Lifetime	hours	<1,000	1,000	5,000

[a] Fuel Cell Seminar Abstracts, 2004, p. 290.

Table 3.4.9. Technical Targets: Auxiliary Power Units (3–5 kW rated, 5–10 kW peak) and Truck Refrigeration Units (10–30kW rated)

Characteristic	Units	2004[a] Status	2006	2010	2015
Specific Power	W/kg	35[b]	70	100	100
Power Density	W/L	35[b]	70	100	100
Efficiency @ Rated Power[c]	%LHV	15	25	35	40
Cost[d]	$\$/\text{kW}_e$	>2,000	<800	400	400
Cycle Capability (from cold start) over operating lifetime	number of cycles	5	40	150	250
Durability	hours	100	2,000	20,000	35,000
Start-up Time	min	60–90	30–45	15–30	15–30

[a] Estimate of current capability based on cell and small stack laboratory developments.
[b] Without power conditioning.
[c] Electrical efficiency only—does not include any efficiency aspects of the heating or cooling likely being provided.
[d] Cost based on high-volume manufacturing quantities (100,000 units/year).

Table 3.4.10. Technical Targets: Sensors for Automotive and Stationary Fuel Cell Systems[a]

All sensors require industrial standard output, e.g., 4~20mA, 1~5V.DC, 0~5V.DC, 0~10V.DC

Sensor	2010 Requirement
Carbon Monoxide	(a) Stored H_2 at 99.999% at transportation fueling station • 0.1 – 0.5 ppm • Operational temperature: <150°C • Response time: 0.1–1 sec • Gas environment: dry hydrogen at 1–700 atm total pressure • Accuracy: ≤2% full scale
	(b) Reformate from stationary fuel processor to PEM stack • 100–1000 ppm CO sensors • Operational temperature: 250°C • Response time: 0.1–1 sec • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: ≤2% full scale
	(c) Between shift reactors and PSA • 0.1–2% CO sensor 250°–400°C • Operational temperature: 250°– 400°C • Response time: 0.1–1 sec • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: ≤2% full scale
Hydrogen in fuel processor output	• Measurement range: 25%–100% • Operating temperature: 70°–150°C • Response time: 0.1–1 sec for 90% response to step change • Gas environment: 1–3 atm total pressure, 10–30 mol% water, 30%–75% total H_2, CO_2, N_2 • Accuracy: ≤2% full scale
Hydrogen in ambient air (safety sensor)	• Measurement range: 1– 5% • Temperature range: –30°C to 80°C • Response time: under 1 sec • Accuracy: <5% full scale • Gas environment: ambient air, 10%–98% RH range • Lifetime: 5 years • Interference resistant (e.g., hydrocarbons)
Sulfur compounds (H_2S, SO_2, organic sulfur)	(a) H_2 to storage, ambient temperature • Operating temperature: up to 300°C • Measurement range: 0.01–0.5 ppm • Response time: <1 min at 0.05 ppm • Gas environment: H_2, CO, CO_2, hydrocarbons, water vapor
	(b) From fuel processor • Operating temperature: up to 300°C • Measurement range: 0.01–0.5 ppm • Response time: <1 min at 0.05 ppm • Gas environment: H_2, CO, CO_2, hydrocarbons, water vapor

Flow rate of fuel processor output	• Flow rate range: 30–300 SLPM (3–25kW) and 800–15,000 SLPM (50–250 kW) • Temperature: 0–100°C • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Ammonia	• Operating temperature: 70–150°C • Measurement range: 0.5–5 ppm • Selectivity: <1 ppm from gas mixtures • Lifetime: 5–10 years • Response time: <1 min at 0.5 ppm • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Temperature	• Operating range: –40°C to 150°C • Response time: in the –40°–100°C range <0.5 sec with 1.5% full-scale accuracy; in the 100°–150°C range, a response time <1 sec with 2% full–scale accuracy • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure • Insensitive to flow velocity
Relative humidity for cathode and anode gas streams	• Operating temperature: 0°C to 120°C • Relative humidity: 20%–100% • Accuracy: 1% full scale • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm
Oxygen in cathode exit	• Measurement range: 0%–50% O_2 • Operating temperature: 30°–120°C • Response time: <0.5 sec • Accuracy: 1% full scale • Gas environment: H_2, CO_2, N_2, H_2O at 1–3 atm total pressure
Differential pressure in fuel cell stack	• Range: 0–1 psi (or 0–10 or 1–3 psi, depending on the design of the fuel cell system) • Temperature range: 30°–120°C • Survivability: –40°C • Response time: <1 sec • Accuracy: 1% of full scale • Other: measure in the presence of liquid and gas phases
Flow rate for direct hydrogen system	• Flow rate maximum: 2500 SLPM for wet H_2 • Flow rate maximum: 1000 SLPM for dry H_2 • Gas environment: H_2 dry (see table 3.4.16 for concentration), 25–100% RH

[a] Sensors for transportation must enable conformation to size, weight, and cost constraints.

Table 3.4.11. Technical Targets: Compressor/Expanders for Transportation Fuel Cell Systems 80-kW_e Unit-Hydrogen					
Characteristic	**Units**	**2004 Status**	**2005**	**2010**	**2015**
Input Power [a] at Full Load, 40°C Ambient Air (with Expander / without Expander)	kW_e	6.3/13.7[b]	6.3/13.7	5.4/12.8	5.4/12.8
Overall Motor/Motor Controller Conversion Efficiency, DC Input	%	85	85	85	85
Input Power at Full Load, 20°C Ambient Air (with Expander / without Expander)	kW_e	5.2/12.4[b]	5.2/12.4	4.4/11.6	4.4/11.6
Compressor/Expander Efficiency at Full Flow (C/E Only)[c]	%	75/80[d]	75/80	80/80	80/80
Compressor/Expander Efficiency at 20–25% of Full Flow (C/E Only) /Compressor at 1.3 PR/Expander at 1.2 PR	%	45/30[d]	55/45	60/50	60/50
System Volume[e]	liters	22[b]	15	15	15
System Weight[e]	kg	22[b]	15	15	15
System Cost[f]	$	700	600	400	200
Turndown Ratio		10:1	10:1	10:1	10:1
Noise at Maximum Flow (excluding air flow noise at air inlet and exhaust)	dB(A) at 1 meter	65	65	65	65
Transient Time for 10–90% of Maximum Airflow	sec	1	1	1	1

[a] Input power to the shaft to power a compressor/expander, or compressor only system, including a motor/motor controller with an overall efficiency of 85%. 80-kW_e compressor/expander unit for hydrogen/air flow – 90 g/sec (dry) maximum flow for compressor, compressor outlet pressure is specified to be 2.5 atm. Expander (if used) inlet flow conditions are assumed to be 93 g/sec (at full flow), 80°C and 2.2 atm.

[b] Projected.

[c] The pressure ratio is allowed to float as a function of load. Inlet temperature and pressure used for efficiency calculations are 20-40ºC and 2.5 atm.

[d] Measure blade efficiency.

[e] Weight and volume include the motor and motor controller.

[f] Cost targets based on a manufacturing volume of 100,000 units per year, includes cost of motor and motor controller.

Table 3.4.12. Technical Targets: Membranes for Transportation Applications

Characteristic	Units	2004 Status	2005	2010	2015
Membrane Conductivity at Operating Temperature Room temperature –20°C	 S/cm S/cm S/cm	 0.10 0.07 0.01	 0.10 0.07 0.01	 0.10 0.07 0.01	 0.10 0.07 0.01
Operating Temperature	°C	≤80	≤120	≤120	≤120
Inlet water vapor partial pressure	kPa (absolute)	50	25	1.5	1.5
Oxygen cross–over[a]	mA/cm^2	5	5	2	2
Hydrogen cross–over[a]	mA/cm^2	5	5	2	2
Cost	$\$/m^2$	65[b]	200	40	40
Durability with cycling At operating temp of ≤80°C At operating temp of >80°C	 hours hours	 ~1000[c] not available[e]	2000	 5000[d] 2000	 5000[d] 5000[d]
Survivability	°C	–20	–30	–40	–40
Thermal cyclability in presence of condensed water		Yes	Yes	Yes	Yes

[a] Tested in MEA at 1 atm O_2 or H_2 at nominal stack operating temperature.
[b] Based on 2004 TIAX Study and will be periodically updated.
[c] Durability is being evaluated. Steady-state durability is 9,000 hours.
[d] Includes typical driving cycles.
[e] High-temperature membranes are still in a development stage and durability data are not available.

Table 3.4.13. Technical Targets: Electrocatalysts for Transportation Applications						
Characteristic	Units	2004 Status		Targets (Stack)		
		Cell	Stack	2005	2010	2015
PGM Total Content	g/kW rated	0.6	1.3	2.67	0.5	0.4
PGM Total Loading[a]	mg PGM/cm^2 electrode area	0.45	0.8	0.7	0.3	0.2
Cost	\$/kW[b]	9	20[c]	40	8	6
Durability with cycling At operating temp of ≤80°C At operating temp of >80°C	 hours hours	 >2000 not available[f]	 ~1000[d] not available[f]	 2000	 5000[e] 2000	 5000[e] 5000
Mass Activity[g]	A/mg$_{Pt}$ @900mV$_{iR-free}$	0.28	0.11	0.30	0.44	0.44
Activity[g]	μA/cm^2 @ 900mV$_{iR-free}$	550	180	600	720	720
Non–Pt Catalyst Activity per volume of supported catalyst	A/cm^3 @ 800 mV$_{IR-free}$	8	not available	50	>130	300

[a] Derived from achieving performance at rated power targets specified in Table 3.4.14. Loadings may have to be lower.
[b] Based on platinum cost of \$450/troy ounce = \$15/g, and loading < 0.2 g/kWe
[c] Based on 2004 TIAX Study and will be periodically updated.
[d] Durability is being evaluated. Steady-state durability is 9,000 hours.
[e] Includes typical driving cycles.
[f] High-temperature membranes are still in a development stage and durability data is not available.
[g] Test at 80˚C; H_2/O_2; fully humidified with total outlet pressure of 150 KPa; anode stoichiometry 2; cathode stoichiometry 9.5.

Table 3.4.14. Technical Targets: MEAs

Characteristic	Units	2004 Status	2005	2010	2015
Operating Temperature	°C	≤80	≤120	≤120	≤120
Inlet water vapor partial pressure	kPa (absolute)	50	25	1.5	1.5
Cost[a]	$/kW	40[b]	50	15	10
Durability with cycling At operating temp of ≤80°C At operating temp of >80°C	 hours hours	 ~1000[c] not available[e]	 2000	 5000[d] 2000	 5000[d] 5000[d]
Survivability Temperature	°C	–20	–30	–40	–40
Total Catalyst Loading (both electrodes)[f]	g/kW (rated)	1.1	2.7	0.33	0.20
Performance @ ¼ power (0.8V)	mA/cm^2 mW/cm^2	200 160	250 200	400 320	400 320
Performance @ rated power	mW/cm^2	600	800	1280	1280
Extent of performance degradation over lifetime[g]	%	10	10	10	10
Thermal cyclability in presence of condensed water		Yes	Yes	Yes	Yes

[a] Based on 2002$ and cost projected to high-volume (500,000 stacks per year).
[b] Based on 2004 TIAX Study and will be periodically updated.
[c] Durability is being evaluated. Steady-state durability is 9,000 hours.
[d] Includes typical driving cycles.
[e] High-temperature membranes are still in a development stage and durability data are not available.
[f] Equivalent total precious metal loading (anode + cathode): 0.1 mg/cm^2 by 2010 at rated power.
Precious metal target based on cost target of <$3/kW precious metals in MEA [@$450/troy ounce ($15/g) and loading of < 0.2 g/kW_e].
[g] Degradation target includes factor for tolerance of the MEA to impurities in the fuel and air supply.

Table 3.4.15. Technical Targets: Bipolar Plates

Characteristic	Units	2004 Status	2010	2015
Cost	$/kW	10	6	4
Weight	kg/kW	0.36	<1	<1
H_2 Permeation Rate	$cm^3\ sec^{-1}\ cm^{-2}$ @ 80°C, 3 atm (equivalent to <0.1 mA/cm^2)	$<2 \times 10^{-6}$	$<2 \times 10^{-6}$	$<2 \times 10^{-6}$
Corrosion	$\mu A/cm^2$	<1[a]	<1[b]	<1[b]
Electrical Conductivity	S/cm	>600	>100	>100
Resistivity[c]	ohm/cm^2	<0.02	0.01	0.01
Flexural Strength	MPa	>34	>4 (crush)	>4 (crush)
Flexibility	% deflection at mid–span	1.5 to 3.5	3 to 5	3 to 5

[a] Based on coated metal plates.
[b] May be as low as 1 nA/cm^2 if all corrosion product ions remain in ionomer.
[c] Includes contact resistance.

Table 3.4.16. Hydrogen Quality

Component	Level
Hydrogen	>99.9
Sulfur	10 ppb
CO	0.1 ppm
CO_2	5 ppm
NH_3	1 ppm
NMHC on a C–1 basis	100 ppm
Particulates	Conform to ISO 14687

3.4.4.2 Barriers

Of the many issues discussed here, cost and durability present two of the most significant barriers to the achievement of clean, reliable, cost-effective systems.

A. Durability. Durability of fuel cell stacks, which must include tolerance to impurities and mechanical durability, has not been established. Tolerance to other impurities, such as sulfur and possibly ammonia, is also necessary. MEA stability for automotive drive cycles has not been demonstrated. Operation at low relative humidity (25-50% RH) and startup from sub-freezing temperatures have not been demonstrated.

To compete against other distributed power generation systems, stationary fuel cells must achieve greater than 40,000 hours durability. Sulfur-tolerant catalysts and membrane materials are required to achieve this durability target, and research must elucidate failure mechanisms. Benchmarking of the state-of-the-art R&D systems is also necessary.

Current fuel processing systems have not achieved required durability, due in large part to the impurities contained in the fuels entering the reformer. Limited data are available on the effects of fuel composition, additives, impurities (e.g., sulfur) and contaminants on fuel processor catalyst and subsystem component durability. The effect of carbon formation on catalyst activity for various fuels and the effect of operating conditions on durability are not adequately quantified. Sulfur removal technology and impurity-tolerant catalysts and/or removal processes are required.

B. Cost. Materials and manufacturing costs are too high for bipolar plates, catalysts, membranes and gas diffusion layers (GDLs). Lower cost, lighter, corrosion-resistant bipolar plates and low-cost, high-performance membranes, and catalysts enabling ultra-low precious metal loading are required to make fuel cells competitive. The use of non-precious metal catalysts will also reduce the cost of MEAs. Low-cost, high-volume manufacturing processes are also necessary.

The cost of fuel processors is high because the operating temperature requires costly high-temperature materials, the low activity of shift catalysts requires large reactors, precious metal catalysts must be used, and the complexity of the fuel processor requires multiple reactors and thermal integration. Substitution of lower-cost materials (particularly reduced Pt or non-Pt catalysts) and components, and integration of subsystems and functions are required to achieve cost goals.

C. Electrode Performance. Voltage losses at the cathode are too high to meet efficiency targets simultaneously with the other targets. Anode and cathode performance depend on precious metal loading, which is currently too high (at the cathode) to meet cost targets. In addition, power densities at the higher voltages required for high-efficiency operation are currently too low to meet cost and packaging targets. Current activities are focused on cathode performance because the kinetics at the cathode are ~100 times slower than at the anode.

D. Thermal, Air and Water Management. Thermal management processes include heat use, cooling, and steam generation. Higher temperature membranes and/or improved heat utilization, cooling, and humidification techniques are needed. The low operating temperature of PEM fuel cells results in a relatively small difference between the fuel cell stack operating temperature and ambient air temperature that is not conducive to conventional heat rejection approaches and limits the use of heat generated by the fuel cell (approximately 50% of the energy supplied by the fuel). More efficient heat recovery systems, improved system designs, advanced heat exchangers and/or higher temperature operation of current systems are needed to utilize the low-grade heat and achieve the most efficient (electrical and thermal) systems, particularly for distributed generation power. Water management techniques to address humidification requirements and maintain water balance are required.

E. **Compressors/Expanders.** Automotive-type compressors/expanders that minimize parasitic power consumption and meet packaging and cost requirements are not available. To validate functionality in laboratory testing, current systems often use off-the-shelf compressors that are not specifically designed for fuel cell applications, resulting in systems that are heavy, costly, and inefficient. Automotive-type compressors/expanders that meet the FreedomCAR and Fuel Cell Partnership technical guidelines need to be engineered and integrated with the fuel cell stack so that the overall system meets packaging, cost, and performance requirements.

F. **Fuel Cell Power System Integration**. The interdependency of fuel cell subsystems is an important consideration in the development of individual components for propulsion and APUs. The interdependency of the system components will affect the packaging, response, and efficiency of the power system. Development of a validated system model and periodic benchmarking of integrated fuel cell power systems, subsystems, and components are required to assess technology status. Ultimately, operation of components and subsystems will be validated in the integrated systems developed outside the Program. Careful system integration is required to achieve overall system efficiency and cost targets. Full-sized, integrated systems with improved catalysts and reactors that demonstrate the required operating characteristics and efficiency for stationary applications must be developed. Maximum fuel processor efficiency is necessary to achieve target efficiencies for economic viability. Data and models for fuel impacts on fuel processor performance and emissions are limited.

G. **Power Electronics.** Distributed generation fuel cell power systems will require energy management strategies and power electronics that enable the fuel cell power system to manage power transients and load-following requirements efficiently and cost effectively. Grid interconnection may also be a major commercialization issue for many distributed fuel cell power applications as with all emerging distributed power generation technologies (grid interconnection issues are being addressed by the Office of Distributed Energy Resources). Priority power management issues include developing a universal dc buss, high-frequency power conditioner, integrated transfer switch and inverter, and grid-independent electronics.

H. **Sensors.** Sensors are required that meet performance and cost targets for measuring physical conditions and chemical species in fuel cell systems. Current sensors do not perform within the required ambient and process conditions, do not possess the required accuracy, range and response time, and/or are too costly. Performance in humid environments is also a concern.

I. **Hydrogen Purification/Carbon Monoxide Cleanup.** A fuel processor must produce high-quality hydrogen to prevent degradation of the fuel cell stack. Liquid fuels contain impurities such as sulfur compounds. These compounds and their derivatives, as well as carbon monoxide, must be removed to prevent loss of performance in the fuel cell. To prevent fuel cell catalyst poisoning, the fuel processor needs to deliver a hydrogen stream with CO levels of less than 10 ppm under most operating conditions and a maximum of 100 ppm during transients and startup. Current CO cleanup systems produce a fuel stream with an acceptable CO level under steady-state operation, but require an extensive control system for transient and startup operation. Improved membranes for hydrogen separation are needed to meet fuel purity requirements under transient and startup operation.

J. Startup Time/Transient Operation. Fuel cell systems take longer to cold start (30 second minimum) compared to other distributed power generation systems, especially backup power systems. Stationary fuel processors start up slowly and do not respond rapidly to variations in power demand. R&D to address startup time through the use of hybrid systems or other viable methods is needed. Fuel cell power plants will be required to meet rapid startup needs and to follow load variations. Some other means of bridging the gap between the current status and 2010 targets must be used, such as hydrogen storage tanks.

3.4.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.4.16. Concerns regarding safety will be addressed within each task in coordination with the appropriate program element. The barriers associated with each task (see Section 3.4.4.2) are also reported.

Table 3.4.16. Technical Task Descriptions

Task	Description	Barriers
Transportation Systems		
1	**Chemical and Physical System Sensors** **Chemical Sensors: Prototype Development** • Measure the CO concentration at the entrance to the fuel cell stack. • Monitor ambient concentrations of hydrogen for safety in the presence of other species found in the ambient air. • Measure the concentration of sulfur compounds such as H_2S, SO_2, and organic sulfur compounds. • Measure the concentration of ammonia in high-humidity stream in the presence of other constituents. • Measure oxygen concentration at the cathode exit. **Physical Sensors: Prototype Development** • Measure the flow rate of hydrogen into the fuel cell at 1–3 atm total pressure. • Fast-response temperature sensors that operate in high humidity gas streams and are insensitive to flow velocity. • Measure the relative humidity of anode and cathode gas streams.	H

2	**Sensors Meeting 2010 Targets** **Chemical Sensors: Verification** • Measure the CO concentration at the entrance to the fuel cell stack. • Determine hydrogen concentration at the fuel cell inlet in the presence of other constituents. • Monitor ambient concentrations of hydrogen for safety in the presence of other species found in the ambient air. • Measure the concentration of sulfur compounds such as H_2S, SO_2, and organic sulfur compounds in the presence of other constituents. • Measure the concentration of ammonia in high-humidity streams and in the presence of other constituents. • Measure oxygen concentration at the cathode exit. **Physical Sensors: Verification** • Devices for measuring the flow rate of hydrogen into the fuel cell at 1–3 atm total pressure. • Fast-response temperature sensors that operate in high humidity streams and are insensitive to flow velocity. • Measure the relative humidity for the anode and cathode gas streams.	H
3	**Benchmarking, Hardware Evaluation, and Analyses** • Test and evaluate fuel cell power systems under simulated automotive drive and rigorous durability cycles. • Quantify fuel cell power system emissions. • Conduct analyses for overall and specific component costs for transportation fuel cell systems	B, F
4	**Air, Water, and Thermal Management** • Develop and test low-cost, high-efficiency, lubrication-free compressors, expanders, motors, motor controllers and blowers (turbo, torroidal intersecting vane) • Investigate and develop advanced heat rejection technologies and materials (compact humidifiers, heat exchangers, and radiators)	D, E
5	**Compressors Meeting 2010 Guidelines** • Verify advanced compressors/motor/expanders and blowers that meet the 2010 targets for weight, volume, performance and cost.	E
6	**Direct Methanol Fuel Cells** • Design and test advanced cathode catalysts with low Pt loading. • Develop membranes and MEAs with reduced methanol crossover. • Build and evaluate improved-performance direct-methanol single cell. • Design and build DMFC stack system with improved power density, efficiency, and water management. • Test and evaluate DMFC stack. • Develop and test DMFCs for consumer electronic devices.	B, C, D, F
7	**Auxiliary/Portable Power** • Advanced methanol oxidation catalyst, and MEAs with low Pt-loading for DMFCs. • Miniature fluid handling technologies for DMFC systems. • Low-cost, high-volume manufacturing processes for auxiliary/portable power fuel cells. • Miniature fuel processors for PEMFC and solid oxide fuel cell (SOFC) systems. • Determine system requirements for fuel cell APUs for HDVs. • Verify fuel cell technologies for APUs (to 30 kW), consumer electronic devices (< 50 W), and off-road systems. • Test and evaluate fuel cell APUs for HDVs under simulated duty and rigorous durability cycles.	A, B, C, F, I

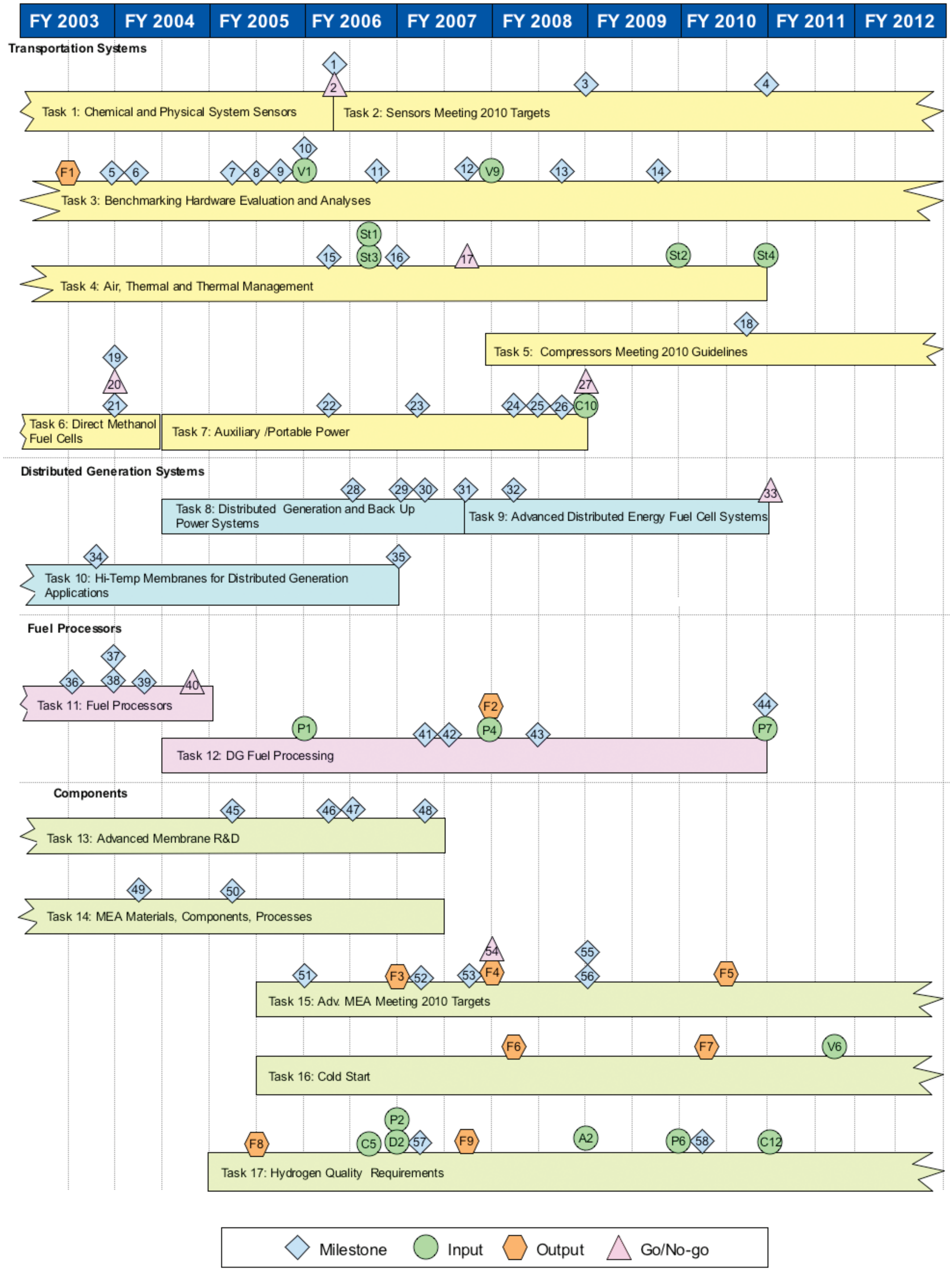
Distributed Generation Systems		
8	**Distributed Generation and Back-up Power Systems** • Stationary fuel cell system that meets the 2005 technical targets for distributed generation systems. • Mitigate technical, commercial, and cost barriers to stationary fuel cells. • CHP fuel cell systems to cost-effectively recover thermal energy to meet some or all of the building's heating/cooling requirements. • Power systems for back-up or peak shaving applications for commercial/industrial operations. • Identify and understand failure mechanisms to enable improvements in reliability and durability. • Work with DER and utility partners to address interconnectivity to grid issues.	A, G, H, J
9	**Advanced Distributed Energy Fuel Cell Systems** • Stationary fuel cell system that can operate on natural gas or LPG at 40% or higher electrical efficiency. • Advanced stationary fuel cell system that can achieve a cold start up time of less than 1 minute. • Demonstrate through accelerated testing a stationary fuel cell system showing potential to achieve >40,000-hour durability. • Test improved heat recovery system that improves net system efficiency. • Advanced heat exchangers, condensers, and humidifiers. • Improve system humidification to reduce overall energy required to humidify gases while reducing size and cost. • Investigate heat generated cooling (such as desiccant cycles).	A, G, H, J
10	**High-Temperature Membranes for Distributed Generation Applications** • Highly conducting, high temperature membranes capable of achieving 100-150°C with improved electrical and mechanical properties. • Demonstrate improved CO tolerance. • Lower cost high-temperature membranes. *Note - This task was initiated under the Fuel Cells for Buildings Program (Office of Power Technologies) and feeds into Task 13	A, D, I
Fuel Processors		
11	**Fuel Processors** • Fuel processing catalysts (reforming, shift, desulfurization, etc.) having higher activities, greater stability, lower cost and that enable lower reactor operating temperatures. • Evaluate alternative fuel processing techniques, such as absorber enhancement. • Complete testing and evaluation of system performance and emissions on conventional and alternative fuels over steady-state and transient operation. • Verify and improve fuel processor model and system analyses.	A, B, F, I, J
12	**Distributed Generation Fuel Processing** • Fuel processing systems that can reform natural gas or LPG to hydrogen for stationary applications. • Fuel processing systems that meet technical and cost targets for 2005. • Advanced water-gas-shift catalysts and reactor designs that meet requirements for operational space velocity.	A, B, F, D, G, I, J,

Stack Components		
13	**Advanced Membrane RD&D (See Task 10)** • Investigate new approaches/electrode structures to achieve good adhesion between new membranes and catalyst layer. • Proton-conducting fuel cell membranes for operation at ≤120°C for transportation. • Improve understanding of nature of local structure in catalyst layer. • Increase knowledge of proton conduction in high-temperature membrane systems. • Membranes with nonaqueous proton-conducting phases for stationary fuel cell membranes for operation at >120°C. • Investigate membranes that can function at low hydration levels, <25%. • Fabricate and test MEAs meeting technical targets in single cells. • Investigate membrane/MEA long-term stability and durability. • Verify advanced membranes in subscale stack.	A, C, D, I
14	**MEA Materials, Components, Processes** • Low-cost polymer membranes having higher ionic conductivity, improved humidification properties, and lower gas permeability than state-of-the-art membranes. • Improved gas diffusion layer on full-size cells. • Investigate the effects of sulfur impurities on catalyst performance. • Design, synthesize, and evaluate alternative catalyst formulations and structures (to reduce or eliminate precious metal loading) for impurity tolerance and oxygen reduction. • Alternative bipolar plate materials/coatings that are low-cost, lightweight, corrosion-resistant, and impermeable. • Fabricate and test MEAs in full-size single cells. • Methods for producing low-cost, high-rate fabrication of fuel cell components (e.g., bipolar plates, membranes, MEAs, and gas diffusion layers). • Verify reproducibility of full-size components produced in high-rate manufacturing processes. • Integrate components in subscale stack system to verify performance, i.e., increased efficiency, power density, and reliability compared with previous development efforts.	A, B, C
15	**Advanced MEA Meeting 2010 Targets** • Incorporate advanced cathode and membrane in MEA with Pt loading at 2010 targets. • Verify advanced MEA in single cell. • Verify advanced MEA in stack. • Demonstrate low-cost, high-volume manufacturing processes for advanced MEAs. • Establish durability of advanced MEAs for 2010 targets for transportation and stationary applications.	A, B, C, D
16	**Cold Start** • Investigate new approaches for water management to mitigate the effects of exposure to subfreezing environment. • Determine kinetics of water phase change at freezing temperatures in fuel cell membranes. • Characterize morphological changes and localized stresses in fuel cell components associated with water phase transition during freezing conditions. • Membrane and gas diffusion layer materials to enhance freeze tolerance and improve subfreezing operation and robustness.	A, B, C, D, H, J
17	**Hydrogen Quality Requirements** • Determine the effects of very low level of sulfur compounds (<100 ppb of SO_2 and <20 ppb of H_2S) on fuel cell performance. • Determine the effects of organic materials such as formaldehyde and formic acid and of combustion diesel fumes on fuel cell performance as a function of impurity concentration and operating temperature. • Characterize the effects of salts (NaCl, $CaCl_2$) on properties of fuel cell catalyst layer, membrane, gas diffusion layer, and graphite flow fields or other bipolar plate materials; quantify effects of low levels of salts on long-term fuel cell performance.	A, B, C, H, I

3.4.6 Milestones

Figure 3.4.2 shows the interrelationship of milestone, tasks, supporting inputs, and technology program outputs for the Fuel Cell Program element from FY 2004 through FY 2010. This information is also summarized in Table B.4 in Appendix B.

Figure 3.4.2. Hydrogen Fuel Cell R&D Milestone Chart



For chart details see next page.

Milestones

1 Complete development and testing of low-cost, high-sensitivity sensors.
2 Go/No-Go: The status of sensors and controls technologies will be assessed and compared with the established technical and cost targets. Based on the assessment and the degree of success, the technologies will be released for use, more development will be indicated, or effort will be terminated.
3 Develop laboratory-scale physical and chemical sensors with improved response time and lower cost.
4 Develop physical and chemical sensors meeting 2010 targets.
5 Deliver model of FCV system.
6 Complete modeling of the availability and economics of platinum group metals.
7 Complete initial evaluation of 25-50-kW advanced integration, atmospheric gasoline reformed system.
8 Quantify fuel cell power system emissions.
9 Evaluate progress towards meeting FY2005 fuel cell cost target.
10 Complete analysis of overall and specific component costs for transportation fuel cell systems.
11 Evaluate progress towards meeting FY2010 fuel cell cost target.
12 Evaluate progress towards meeting FY2010 fuel cell cost target.
13 Evaluate progress towards meeting FY2010 fuel cell cost target.
14 Evaluate progress towards meeting FY2010 fuel cell cost target.
15 Complete development of heat rejection technologies (compact humidifiers, heat exchangers, and radiators).
16 Complete development and testing of low-cost, high-efficiency, lubrication-free compressors, expanders, blowers, motors, and motor controllers.
17 Go/No-Go: The status of air management and thermal management technologies will be assessed and compared to the established technical and cost targets. Based on the assessment and the degree of success, the technologies will be released for use, more development will be indicated, or effort will be terminated.
18 Complete development of compressor, expander, motor blower and motor controller meeting 2010 targets.
19 Identify main routes of DMFC performance degradation.
20 Go/No-Go: Decision to discontinue DMFC R&D for transportation applications.
21 Down-select design scenarios for vehicular fuel cell APUs for further study.
22 Complete evaluation of fuel cell system designs for APUs.
23 Complete design of filtration unit for off-road applications.
24 Evaluate 3-10 kW APU system towards meeting 80 W/kg and 80 W/L targets.
25 Evaluate 20-50 W portable power fuel cell system towards meeting 2006 targets.
26 Portable power fuel cell technology available for industry evaluation.
27 Go/No-Go: Decision on whether to continue auxiliary power, portable power and off-road R&D based on the progress towards meeting 2010 targets.
28 Complete testing on 50 kW stationary beta module system.
29 Complete economic analysis report.
30 Demonstrate prototype back up power system.
31 Complete 15,000 hour, stationary fuel cell system test.
32 Demonstrate the effective utilization of fuel cell thermal energy for heating to meet combined heat and power (CHP) efficiency targets.
33 Go/No-Go: Decision on whether to continue stationary fuel cell system based on progress towards meeting durability, cost and electrical efficiency simultaneously.
34 Demonstrate performance (600 mV at 400 mA/cm^2) of an ultra-thin membrane (< 75 µm) in an MEA under atmospheric conditions at 120°C in a 30-cm^2 cell.
35 Complete full-scale MEA evaluation in short stack.
36 Demonstrate fuel-flexible fuel processor meeting year 2005 targets for efficiency, power density and specific power. Measure startup capability.
37 Verify quick-start concept in brass-board prototype system demonstrating capability to meet 2010 startup technical target.
38 Verify small scale, microchannel reformer.
39 Fabricate prototype ion transport membrane module.
40 Go/No-Go: Decision to discontinue fuel processing R&D.
41 Verify fuel processing subsystem performance for distributed generation towards meeting system targets for 2010.
42 Absorption-enhanced natural gas reformer start-up/shut down cycle, transient and durability testing.
43 Develop base metal shift catalysts that enhance conversion to hydrogen and reduce conversion to methane (<1% methane).
44 Develop tolerance of reforming catalysts to fuel containing 1 ppm sulfur.
45 Evaluate 120°C membrane in MEA/single cell.
46 Evaluate 120°C MEA in <10 kW stack.
47 Demonstrate MEA in single cell meeting 2005 platinum loading and performance targets.
48 Evaluate first generation 150°C membrane in MEA/single cell.
49 Evaluate reproducibility (physical and performance) of full-size bipolar plates in high-rate manufacturing processes.
50 Evaluate reproducibility (physical and performance) of MEAs in high-rate manufacturing processes.
51 Initiate 2,000-hour test with advanced membrane & standard GDL.
52 Develop 120°C membrane for operation at < 25% RH.
53 Complete 2,000 hour durability test of advanced MEA for stationary fuel cell application.
54 Go/No-Go: Evaluate precious metal reclamation processes to determine whether to scale-up or terminate.
55 Develop technology for platinum group metal recycling.
56 Evaluate a MEA running on re-manufactured catalyst coated membranes.
57 Develop a method for cleaning sulfur-poisoned platinum catalyst layers in stacks, with minimum interruption of fuel cell operation.
58 Develop a method for cleaning sulfur- and nitrogen-oxide poisoned platinum catalyst layers in stacks, with minimum interruption of fuel cell operation.

Outputs

F1 Output to Systems Analysis and Systems Integration: Develop a critical analysis of well-to-wheels studies of fuel cell system performance, efficiency, greenhouse gas emissions, and cost.
F2 Output to Production: Research results of advanced reformer development.
F3 Output to Technology Validation: Laboratory PEM technology with 2,000 hours durability.

F4 Output to Technology Validation: Complete 4,000 hour testing of advanced MEA for stationary and transportation applications.
F5 Output to Technology Validation: Laboratory PEM technology with 5,000 hours durability.
F6 Output to Technology Validation: Verify cold-start in 60 s of short stack.
F7 Output to Technology Validation: Technology short stack survivability at -40°C.
F8 Output to Systems Analysis and Systems Integration: Develop preliminary hydrogen purity/impurity requirements.
F9 Output to Systems Analysis and Systems Integration: Updated hydrogen purity/impurity requirements.

Inputs

V1 Input from Technology Validation: Validate maximum fuel cell system efficiency.
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
St1 Input from Storage: Compressed and cryogenic liquid storage tanks achieving 1.5 kWh/kg and 1.2 kWh/L.
St3 Input from Storage: Complex hydride integrated system achieving 1.5 kWh/kg and 1.2 kWh/L.
St2 Input from Storage: Advanced compressed/cryogenic tank technologies.
St4 Input from Storage: Full-cycle, integrated chemical hydride system meeting 2010 targets.
C10 Input from Codes and Standards: Final draft standard (balloting) for portable fuel cells (UL).
P1 Input from Production: Hydrogen production technology for distributed systems using natural gas with projected cost of $3.00/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
P4 Input from Production: Hydrogen production technology for distributed systems using natural gas with projected cost of $2.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
P7 Input from Production: Hydrogen production technologies for distributed systems using natural gas with projected cost of $1.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
V6 Input from Technology Validation: Validate cold start-up capability (in a vehicle with an 8-hour soak) meeting 2005 requirements (specific cold-start energy).
C5 Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.
P2 Input from Production: Assessment of fuel contaminant composition.
D2 Input from Delivery: Hydrogen contaminant composition and issues.
A2 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.
P6 Input from Production: Assessment of fuel contaminant composition.
C12 Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.